An Assessment of the United States Measurement System:

Addressing Measurement Barriers to Accelerate Innovation

Appendix I

Summary Results of Inferential Analysis of Measurement Needs

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Summary Results of Inferential Analysis of Measurement Needs

High-level summaries of the results of the inferential analysis process for each sector/technology area were developed provisionally as a two page documents. These were further distilled before inclusion in the report document. They contained the following:

- brief summaries of the sector/technology area
- technological innovations that could benefit from solutions to the measurement problems identified in the measurement needs associated with the sector/technology area
- the number of case study measurement needs (Appendix B) and technology roadmap measurement needs (Appendix C) used in the analysis
- Findings (declarative statements) resulting from the analysis
- other observations (declarative statements not rising to the level of rigor required of Findings) were also included in most of the summaries.

These two page documents are contained in the remainder of this appendix.

Building and Construction

Building and construction is a $1.4 trillion industry (2005) employing 10 million people in 1 million companies throughout the United States. The construction industry is a key component of the U.S. economy and is vital to its continued growth. Investment in plants and facilities, in the form of construction activity, provides the basis for the production of products and the delivery of services. Investment in infrastructure promotes the smooth flow of goods and services and the movement of individuals. Investment in housing accommodates new households and allows existing households to expand or improve their living conditions. Construction activities affect nearly every aspect of the U.S. economy.

The *Building and Construction* sector/technology area is driven more than any other industry by codes and standards. Nearly all buildings are subject to the requirements of building codes prior to approval for construction. Although the codes are administered by local and state governments, the codes are all derivatives of two model building codes that are developed nationally by private sector organizations populated by code officials from across the country. The codes themselves cite numerous standards developed by SDOs. The building codes largely contain minimum requirements in prescriptive language. This is a significant barrier to technological innovation since designers and builders normally stick to the minimum specified performance. Performance requirements, standards, and codes are a growing trend and when fully implemented, will be much more supportive of technological innovation.

Among the technological innovations in *Building and Construction* that would benefit from solutions to the measurement problems documented in this assessment are:

- Building materials, components, equipment, and structures that enhance fire safety, durability, energy efficiency, and indoor air quality.
- Distributed energy systems utilizing fuel cells and/or photovoltaics.
- Automation and interoperability of construction software, tools and processes.
- Enhanced fire detection and suppression systems that integrate traditional sensors, video detection, and intelligent signal processing.
- Energy-efficient LED lighting in building applications.
- Advanced sensors/building automation systems to optimize building operations.

Data and Results

The set of measurement needs for this sector/technology area consisted of 23 MNs and 18 RMNs, the latter generated from 10 roadmaps. As results for this sector/technology area, the *inferential analysis process* yielded the following *findings*, which are firm conclusions verified by industry.

Findings

The integration of various systems within a building is needed to minimize life-cycle costs while ensuring a safe environment. Building systems integration requires real-time measurements of numerous parameters, and increased collaboration among *measurement solution providers* in the *building and construction* sector/technology area.

Building operators currently lack the real-time information necessary to optimize the operation of their buildings. This information includes real-time measurements of critical parameters such as energy usage, maintenance, structural integrity, indoor air quality, and fire safety. Improvements in building envelope and equipment performance, IT interoperability, and sensor technology were identified as key to the

integration of building systems. Wireless sensor technology will greatly assist in transferring data to numerous building systems. The wide range of measurement needs involved points to the need for increased collaboration among all *measurement solution providers*.

The lack of reliable and unbiased performance data slows the adoption of new and innovative technologies in the *Building and Construction* sector/technology area. Standard test methods are needed to capture desired performance data. Joint efforts by SDOs and the public and private sectors to develop standard test methods can ensure that unbiased performance measures are in place in a timely manner.

Thirty-five percent of the measurement needs in the *Building and Construction* sector/technology area were identified at the marketing *stage of technological innovation*, about three times as frequently as those documented across all sector/technology areas taken together, indicating that the marketing *stage of technological innovation* is a critical point for realizing technological innovation in this sector/technology area. The lack of reliable and unbiased performance data slows the adoption of new technologies as code officials are reluctant to accept innovative technologies without proven performance. Nearly half (47%) of measurement needs identified in technology roadmaps in the sector point to standards as a solution. Standards-developing organizations are identified as the third most frequent solution provider in the *Building and Construction* sector/technology area (12.3%), compared to 4.3% across all of the sector/technology areas taken together. More than half (52%) of the MNs cite competition and limited resources as roadblocks for industry to develop performance measures. The public sector and SDOs are cited as solution providers in 64% of the measurement needs in the *Building and Construction* sector/technology area and would play an important role in developing the needed performance measures.

The lack of validated models and data are identified as significant barriers to technological innovation in the *Building and Construction* sector/technology area. Models and performance data are playing an increasingly important role in supporting applications of innovative technology as the sector shifts toward greater reliance on performance-based standards.

Nearly two thirds (64%) of the measurement needs documented for the *Building and Construction* sector/technology area identified lack of modeling capability as a significant barrier to technological innovation. Data needs are cited in 56% of the measurement needs. These needs include collection techniques and test, reference, and validated data. Data are needed both for the development and validation of predictive models, as well as for benchmarking and verifying new materials, components, equipment, and systems technologies.

Regulations—in the form of building and fire codes—are a major driver of measurement needs in the *Building and Construction* sector/technology area. Code officials, operating at the state and local levels, require proof that innovative products proposed for installation meet health and safety requirements outlined in code documents.

Nearly half (43%) of the measurement needs noted in the *Building and Construction* sector/technology area roadmaps were at least partially driven by regulatory requirements. Although only three of the measurement needs explicitly cited regulations as either being a *driver or barrier* to technological innovation within the sector, nine additional measurement needs (12 of 23) cited consensus standards as a solution to a *measurement problem*. Standards apply in the *Building and Construction* sector/technology area when adopted into code by a state or local regulating body.

Chemicals

The *Chemicals* sector/technology area includes the manufacture of chemicals, biological processing of chemicals and materials, and continuous manufacturing of fluids. (*Pharmaceuticals* is included in *Health Care including Bioimaging* for this assessment.) The use of chemicals impacts nearly every sector of the U.S. and world economies. The United States is the number-one producer of chemistry products in the world, accounting for 23% of total world chemicals production. This sector/technology area generates $550 billion a year (2005), produces more than 70,000 products, and directly employs nearly 900,000 people. It is the nation's largest exporting sector, with $109.3 billion in exports that account for 10 cents of each dollar of U.S. exports. This sector/technology area is a large energy user, consuming approximately 7% (1999) of total U.S. output. It also is capital intensive and heavily regulated.

The measurement needs included in the *Chemicals* sector/technology area are diverse. The industry is confronted with measurement challenges driven both by the need to adapt mature process technologies to manufacture new products, and to develop and use new processes to make new and current products with greater efficiency.

Among the technological innovations in *Chemicals* that would benefit from solutions to the *measurement problems* documented in this assessment are:

- Advances in process control capabilities that include innovations to the area of process simulation for both existing and new chemical processes and in-line sensing of process conditions and parameters.
- Shifting of raw material sources from a primarily petroleum-based to a much more mixed base that significantly includes biologically derived sources.
- Utilization of nanotechnology for advancing chemical and bio-chemical manufacturing.
- Measurement and characterization tools and standards supporting improved understanding of structure-function relationships.

Data and Results

The set of measurement needs for this sector/technology area consists of 22 MNs and 27 RMNs, the latter from 14 technology roadmaps. As results for this sector/technology area, the *inferential analysis process* yielded *findings* and *other observations*. The *findings* are firm conclusions verified by industry. The *other observations* are provisional conclusions that are suggested by the MN data and considered to be significant but, because of the limited sample of data, do not rise to the level of *findings*.

Findings

New sensor technologies for in-line, real-time, and continuous monitoring of process variables in chemically aggressive environments are needed to overcome technological barriers to manufacturing process innovation.

Sensor technology needs are identified by 25% of the 27 RMNs for various process control and production applications with ~70% of these citing the current unavailability of sensor technologies for production-level applications. Application areas include sensors for energy metering, corrosion detection, and product quality. Sensor attributes cited to be required are robust, reliable, accurate, in-line, and non-invasive. Public institutions are major contributors (59%) to measurement solutions development. Accuracy, resolution, reliability, and speed represent 38% (23 of 60) of the *measurement*

problems identified within MNs. Degradation of materials comprising process equipment, including corrosion, is identified as a significant problem, having both health and safety implications. Sensing/detection of materials degradation was identified particularly. There is a lack of materials degradation measurement technologies, which perhaps indicates the need to improve the scientific knowledge base upon which new measurement technologies could be developed.

New measurement technologies with chemical specificity at the nanoscale, surpassing the limits of detection and sensitivity of current techniques, are needed to overcome *measurement problems* to technological innovation in nanotechnology.

Twenty-two percent of the MNs (5 of 22) and of the RMNs (6 of 27) in this sector/technology area identify problems with making chemically specific, nanoscale measurements as a barrier to technological innovation. MNs include imaging technologies, the measurement of inter-molecular and inter-atomic forces, determination of nanoscale properties, high throughput nano-screening, and reference materials for properties measurements. Nearly half (46%) of MNs identify accuracy as a *measurement problem* with approximately one-third identifying development of measurement technology, measurement methods, and standards as *measurement solutions*. One RMN states explicitly that current measurement methods are reaching their limits of detection and resolution and are inadequate for some current applications. *Measurement solution providers* are most often identified in the public sector (56%), where pre-competitive research is needed to produce an expanded science base for new measurement technologies.

Other Observations

- Regulation will drive new measurement requirements that industry must meet in the future. Public concerns have significant influence on regulation. Recent EU Regulations on hazardous substances in electrotechnical products and on in-vitro diagnostic devices show how regulation drives the need for new measurement standards along the entire supply chain affecting these products. Public health and safety and environmental concerns are expected to continue to impact the need for technological innovations. Much of these will involve measurement problems that can be overcome through improvements to measurement instruments and measurement methods.

Defense and Homeland Security

The United States spends about $100 billion per year on Homeland Security in addition to that spent on Defense. This amount includes the services of federal, state, and local law enforcement and emergency services. Nearly three million state and local first responders regularly put their lives on the line to save others and make the nation safer. For the private sector, business continuity is a critical concern. Since 85% of the physical infrastructure in the United States is owned by the private sector, most expenditures for infrastructure protection are borne by businesses. Private business, a key source of technological innovation, spent approximately $55 billion annually on security prior to the attacks of September 11, 2001. Since that time, the expenditures of private businesses to fight terrorism have increased dramatically.

Defense and Homeland Security technologies can be categorized into two distinct areas: those used for detection and screening, and those used to improve the safety and effectiveness of first responders. Additional detail on this sector/technology area can be found in the Disaster-First Responder section of Appendix F.

Among the technological innovations in *Defense and Homeland Security* that would benefit from solutions to the *measurement problems* documented in this assessment are:

- Advanced sensors for chemical and biological agents, nuclear radiation, and explosives.
- Enhanced first responder clothing, locator systems, and communications.
- Advanced user interfaces for homeland security and first responder technology.
- Improved visible and infrared video surveillance.
- Enhanced millimeter-wave terahertz and hyper-spectral imaging systems.
- Wireless communication systems, chip-scale atomic clocks, and chemical detection.

Data Results

The set of measurement needs for this sector/technology area consists of 35 MNs and 31 RMNs, the latter from 6 roadmaps. As results for this sector/technology area, the *inferential analysis process* yielded *findings* and *other observations*. The *findings* are firm conclusions verified by industry. The *other observations* are provisional conclusions that are suggested by the MN data and considered to be significant but, because of the limited sample of data, do not rise to the level of *findings*.

Findings

There is a significant need for accurate and standardized methods to evaluate system performance for existing technologies under field conditions. By enhancing evaluation techniques and methods of testing for existing technologies, a number of *Defense and Homeland Security* measurement needs can be addressed.

There are a significant number of existing technologies that are being modified to better meet the needs of *Defense and Homeland Security* personnel. Examples are first responder locator systems, radio communication systems, urban search-and-rescue robotics, and infrared camera systems. System performance under actual "field" conditions is critical due to the diversity of both the users and technologies employed. Unfortunately, a lack of performance metrics for these technologies makes it difficult to quantify their performance under "field conditions."

System performance is noted as the *measurand* of interest over three times more often in this sector than in all of the economic sectors/technology areas (24% versus 7%). As procurement decisions are typically linked to system performance verification, the lack of system performance metrics may result in delayed deployment of cited technologies.

New measurement technologies must be developed to support development and application of emerging technologies in the *Defense and Homeland Security* sector/technology area. Measurement needs for emerging technologies are generally different than those of existing technologies.

In 56% of the measurement needs, the *technological innovation at stake* is a measurement technology innovation. Examples include sensors, on-chip wireless communications, atomic clock chips, wireless communication systems, hyper-spectral and millimeter-wave terahertz imaging systems, and spectroscopic explosive detection. More than 90% of the measurement needs that addressed emerging technologies in the *Defense and Homeland Security* sector/technology area place the *measurement problem* that poses a technical barrier at the applied R&D *stage of technological innovation.*

Other Observations

- It is in the interest of *Defense and Homeland Security* sector/technology area developers to bring together the various technology user groups to help define commonality among measurement needs.
- Small-market demands for a portion of the *Defense and Homeland Security* technologies cited within the measurement needs may be a barrier to their development and deployment.
- In the area of first responders, users include firefighters, medical personnel, and law enforcement personnel. Understanding and serving the needs of technology providers and users of first responder and homeland security technologies may be difficult due to fragmentation of these communities.

Discrete-Part Manufacturing Including Automotive

The *Discrete-Part Manufacturing* sector, of which the Automotive industry is a significant part, involves the production and assembly of materials and components, ranging in size from nanometers to hundred of meters, into commercially available consumer and industrial products. This sector/technology area is complex, with thousands of entities organized into multi-level supply chains. Manufacturing at large is a $1.5 trillion industry, employing 14.2 million people. The U.S. automotive manufacturing industry is a $120 billion industry and the third-largest manufacturing industry behind food manufacturing and computer and electronics. Additional information on the automotive industry sector is provided in Appendix F.

Among the technological innovations in *Discrete-Part Manufacturing Including Automotive* that would benefit from solutions to the *measurement problems* documented in this assessment are:

- Realization of making the first part, and every part thereafter, correctly.
- Manufacture of micro-scale and nano-scale discrete parts.
- Seamless and inexpensive hardware and software interoperability.
- Advanced vehicle safety systems.
- Semiconductor production, following the ITRS projections.
- Manufacture of flexible electronics.
- Production of hydrogen fuel cells.

Data Results

The set of measurement needs for this sector/technology area consists of 62 MNs and 22 RMNs, the latter from 8 roadmaps. As results for this sector/technology area, the inferential analysis process yielded findings and other observations. The findings are firm conclusions verified by industry. The other observations are provisional conclusions that are suggested by the MN data and considered to be significant but, because of the limited sample of data, do not rise to the level of findings.

Findings

The solution to an important class of *measurement problems* in manufacturing is development of new measurement technology for high-accuracy characterization of the dimensioned 3D geometry of manufactured products across a spectrum of sector, technology, and application areas.

Among the 62 MNs in this data set, the most frequently cited *measurement solutions* are development of measurement technology (43%), measurement instrument (24%), measurement method (24%), and standards (33%), while the most frequently cited *measurement problems* are accuracy (60%) and resolution (30%).
The *measurand* is cited as physical in 44% of the MNs.

Twenty one percent of the MNs cite problems in the measurement of complex shape. In the automotive sub-sector of manufacturing, these problems with the measurement of complex shapes include: auto bodies, engine casings, and cylinder heads, flexible components such as harnesses and hoses; and micro-machined parts such as fuel injectors.

Inspection of the MNs tagged specifically for the *Discrete-Part Manufacturing Including Automotive* sector/technology area revealed a broad range of technologies and applications with a low concentration of MNs in any one

area. The product technologies for which *measurement problems* to technological innovation have been identified include: machined parts, stampings, automobile fuel injectors, flexible components of autos such as harness assembles and hoses, aspheric optical lenses, computer hard disc drives, and nano-manufactured parts and devices. Inspection of the 50 MNs dealing with computer data storage devices and systems reveals that nearly half of all *measurement problems* relate to dimensional measurement. M*easurement problems* associated with geometry and dimensions of 3D features are also found in the *Electronics and IT Hardware* and *Semiconductor Electronics* sector/technology areas.

The absence of measurement technologies for accurate in-line and real-time measurement of physical attributes of manufactured parts and assemblies, applicable across a spectrum of applications, poses a barrier to technological innovation.

Thirty-one percent of the individual MNs, as well as 13 RMNs, describe a need for real-time and/or in-line measurements. Within this set of MNs related to real-time and/or in-line measurements, development of measurement technology is the most frequently identified measurement solution (74%), while accuracy (63%), resolution (32%), reliability (32%), and speed (32%) are the most frequently identified *measurement problems*. Among the 43 MNs in this data set that identify the *measurement problem* as being at the applied research *stage of technological innovation*, development of measurement technology (49%) and measurement instrument (35%) are the most frequently identified *measurement solutions*. Of these 43 MNs, 47% identify the *technological innovation at stake* as a *measurement innovation*.

It was noted by industry experts asked to authenticate these two findings that both would apply to aspects of continuous manufacturing as well as to discrete manufacturing.

Other Observations

- In addressing *measurement problems*, the *Discrete-Part Manufacturing Including Automotive* sector/technology area could benefit from more industry collaboration when dealing with pre-competitive technical issues.
- Despite the increasing prevalence of IT in manufacturing innovation and control, the need for physical measurements for both validation and input into models remains significant throughout the product cycle. There is also the related need to advance data acquisition, analysis, and representation, to support manufacturing innovation. The USMS has not outgrown the need for physical metrology, as these measurements continue to be used in increasingly sophisticated IT-based manufacturing systems.
- There is a need for better nano-scale characterization. Optical techniques may be a solution.

Electronics and IT Hardware

The *Electronics and IT Hardware* sector/technology area is broad and enabling. In this assessment IT hardware includes component-level hardware, active and passive devices, systems, and end-user products. According to the International Electronics Manufacturing Initiative (iNEMI), electronics products include portable and consumer products, office and business systems, telecommunications products, medical devices, automotive products, and defense/aerospace products. The world electronics market is forecast by the market research firm In-Stat to be worth $1.5 trillion by the year 2007 and is forecast to continue to expand at a rate faster than the world economy as a whole.

Among the technological innovations in *Electronics and IT Hardware* that would benefit from solutions to the *measurement problems* documented in this assessment are next-generation electronic and IT products that include:

- IT and communications instrumentation.
- Fiber optics and optoelectronics.
- Superconducting electronics.
- Radio-frequency electronics.
- Computer data storage devices and systems.
- Smart sensors.
- Microelectromechanical systems (MEMs) and nanoscale electronic devices.
- Quantum computing systems.

Data Results

The set of measurement needs for this sector/technology area consists of 92 MNs and 19 RMNs, the latter from 7 roadmaps. As results for this sector/technology area, the inferential analysis process yielded *findings* and *other observations*. The *findings* are firm conclusions verified by industry. The *other observations* are provisional conclusions that are suggested by the MN data and considered to be significant but, because of the limited sample of data, do not rise to the level of *findings*.

Findings

A systems-level "measurement gap" has emerged, which impedes this sector/technology area's ability to innovate in the current environment that is characterized by distributed companies collaborating to produce integrated systems.

Increased specialization and complexity of the supply chain in this sector/technology area accentuate the need for reliable, widely available, standards-based measurement and test technologies for assessing systems-level performance of products. This sector/technology area has traditionally relied on component-level measurement improvements to advance measurement infrastructure. Electronic products are typically built from a set of building-block components. The importance of component measurements is reflected in the fact that of all the MNs citing component suppliers as sources of *measurement solutions*, a full 72% are addressing electronics issues. But equally important is the emerging recognition (reflected in at least a dozen MNs) that the complexity of systems-level issues requires new measurement technology.

A systems-level solution requires both comprehensive measurements at the components level and advanced systems-level metrics. In the past, when electronics manufacturers produced their own components in-house, information could be

shared among the component- and systems-level engineers. The move away from vertically integrated companies has created a resource and knowledge shortage between the component and system domains, since outsourced margins are too thin to allow component providers to create innovative measurement technology. In the current environment, competition is an additional barrier to the coordination needed for the development of measurement technology, as component providers strive to differentiate their products in a commodity market.

The *measurement problems* in the computer data storage area represent measurement issues with the state of the art of electromechanical systems and their requirements for dimensional, magnetic, and optical characterization with spatial resolutions at the nanoscale.

Thirty-five percent more MNs identified physical rather than electronic/electrical properties as the *measurand* in need of improved measurement capability, and approximately 20% of the *Electronics and IT Hardware* MNs required measurement of some parameter with spatial resolution on the order of 0.1-100 nanometers. These data reflect the continuing emphasis on miniaturization in order to create devices with nanoscale features that exploit new physics and functionality that emerge at the nanoscale. This need is pervasive across the electronics industry, with the emphasis on shrinking device dimensions, and was specifically highlighted in approximately a third of the MNs in this sector/technology area, dealing with one specific type of hardware for information technology—computer data storage devices and systems (hard-disk drives, magnetic-tape, and optical memory systems). Additional detail on the data storage technology area can be found in Appendix F.

Other Observations

- The specialization and increased complexity of the supply chain accentuates the need for stable, widely available, standards-based measurement and test technologies.
- The drive toward miniaturization across industries will require innovative measurement capability at the nanoscale in the *Electronics and IT Hardware* sector/technology area. This sector/technology area is a leader in engineering nanoscale heterogeneous structures and, as a result, the electronic fabrication platform is a launching point for developing a breadth of nanoscale technologies.
- The assessment data reported that the *Electronics and IT Hardware* sector/technology area accounted for 65% of all known private efforts and 38% of all known public and private efforts addressing measurement needs. This high percentage of publicly known efforts may be a reflection of the industry's history of roadmapping and consortia, and the sector's willingness to collaborate on pre-competitive applied research measurement issues.
- Foreign regulatory requirements generate domestic measurement needs and pose unique barriers to technological innovation. U.S. industry tends to be under-engaged in the kind of policy debates now occurring primarily in other countries, and thus is slow to innovate in response to foreign regulations. The nation may pay an extremely high price for this reactive stance in time-to-market.
- The measurement needs collected reflect those that are most visible, either because they represent a potential development or production roadblock, or because their solution could make volume production more profitable. It is unclear how much technological innovation is lost during the earliest stages because small manufacturers are unable to overcome these *measurement problems* on their own.

Energy, Power, and Environment

The *Energy, Power, and Environment* sector/technology area covers those portions of the economy involved with the generation and distribution of energy and power, and environmental monitoring and pollution control issues. The segments included are renewable energy, electrical power generation, oil and gas extraction, advanced energy utilization technologies, power distribution, and environmental monitoring. The review of technology roadmaps and case-study measurement needs for the *Energy, Power, and Environment* sector/technology area revealed specific measurement issues in diverse applications. Measurement needs relate to energy sources, including photovoltaic, fuel cells, bioenergy, wind, and fossil fuels from hard-to-access deposits. Advanced energy utilization technologies involve topics such as solid-state lighting and advanced-refrigeration techniques, which currently use significant amounts of energy. Power distribution ranged from electrical power transmission to storage and metering of hydrogen. Environmental monitoring ranged from global satellite monitoring systems to local sensors for assuring regulatory compliance.

Among the technological innovations in *Energy, Power, and Environment* that would benefit from solutions to the *measurement problems* documented in this assessment are:

- Hydrogen power; improved methods for the distribution of electricity, including the development of superconducting wires and tools for measuring power grid dynamics.
- Visible light emitting diodes (LEDs) for general lighting.
- Fusion energy through the use of tokamaks, a torus-shaped device utilizing magnetic confinement of extremely hot plasma.
- Photovoltaic/solar cell technologies; new energy-efficient refrigeration techniques.
- High-resolution remote sensing techniques for weather forecasting, climate monitoring and finding new sources of energy.
- Advanced power cycles—the conversion of mechanical energy derived from combustion to electrical power, for improved efficiency with lower emissions.

Data and Results

The set of measurement needs for this sector/technology area consists of 27 MNs and 49 RMNs, the latter from 14 technology roadmaps. As results for this sector/technology area, the *inferential analysis process* yielded *findings* and *other observations*. The *findings* are firm conclusions verified by industry. The *other observations* are provisional conclusions that are suggested by the MN data and considered to be significant but, because of the limited sample of data, do not rise to the level of *findings*.

Findings

Many measurement needs associated with traditional fuel and power sources reflect extensive regulatory requirements, while emerging technology for alternative fuel and power sources reflect the anticipation of future regulation.

Regulations are usually designed to measure some key aspect of performance, cost, or environmental impact. In this sector/technology area, one third of the RMNs (16 of 49) directly indicate regulation as an issue. In nearly half of the technology roadmaps identifying regulation as an issue, *measurement problems* are associated with environmental monitoring. Fifty-two percent of the *Energy, Power, and Environment* RMNs identified measurement solutions that are sensor-related. Nearly half (48%) of the MNs deal with the metering of quantities of energy or

the energy efficiency of products. The high frequency of accuracy, data, and lack of fundamental knowledge as *measurement problems*, and development of measurement technology and research for measurement science as *measurement solutions*, is interpreted as an indicator that further supports assertions that measurement science and innovation in measurement technology are means to address this problem. Much of the measurement innovation is associated with emerging technologies, such as those found in issues related to the hydrogen economy.

In case-study measurement needs and roadmap measurement needs related to the hydrogen economy, *measurement problems* occur at all *stages of technological innovation*.

The development of a hydrogen economy is currently receiving greater emphasis than the development of other alternative technologies. Twenty-six percent of MNs and 18% of RMNs are associated with fuel-cell development and/or hydrogen fuel distribution. The MNs and RMNs were associated with all four *stages of technological innovation*, applied research, production, market, and end-use stages. The distribution among MNs was slanted toward applied R&D, in the ratios of 3:2:1:1. RMNs emphasize the production, market, and end-use *stages of technological innovation* in the ratios 0:3:3:2.

Other Observations

- The greatest concentration of measurement technology needs appear in the applied research *stages of technological innovation*. Often, the measurement technology needed requires measurement innovation. Technology developers want reliable, accurate, standardized measurements before the prototype moves to production.

Health Care Including Bioimaging

The United States spends close to $2 trillion per year, representing 20% of the U.S. economy, on health care. The Department of Labor's Bureau of Labor Statistics indicates that health care is the fastest growing occupational field in the nation and predicts a 33% growth by 2015. Technological innovations that increase capabilities or reduce costs in health care translate quickly to benefits and savings for the nation. For example, the Agency for Health Care Policy and Research reports that preventable costs total more than $20 billion per year and the electronic integration of health care information systems is projected to save $70 billion per year.

Health Care Including Bioimaging in this analysis includes bio-imaging, bio-informatics, clinical diagnostics, health and safety, and pharmaceuticals, with the major drivers for technological innovation being improved quality of life and cost of health services. Additional information on the bioimaging technology area can be found in Appendix F.

Among the technological innovations in *Health Care Including Bioimaging* that would benefit from solutions to the *measurement problems* documented in this assessment are:

- Advanced DNA analysis using lab-on-a-chip technology.
- Sensor-based proteomics for early cancer detection.
- New imaging modalities in MRI (magnetic resonance imaging).
- Systems for lower-cost diagnosis and monitoring of bone health.
- Implanted devices for metered delivery of insulin.
- Self-assembly of soft nano-materials for bone and tissue replacement.
- Real-time interactive video/audio telemedicine.
- Reliable and integrated communications among health care systems.

Data and Results

The set of measurement needs for this sector/technology area consisted of 77 MNs and 37 RMNs, the latter generated from 9 roadmaps. As results for this sector/technology area, the **inferential analysis process** yielded *findings* and *other observations*. The *findings* are firm conclusions verified by industry. The *other observations* are provisional conclusions that are suggested by the MN data and considered to be significant but, because of the limited sample of data, do not rise to the level of *findings*.

Findings

The same *peasurement problem* – the combination of lack of accuracy and lack of fundamental knowledge – identified as having the same solution and potential solution providers impedes both medical researchers' development and clinicians' use of new medical technologies.

Of the 185 *measurement problems* identified in the 77 measurement needs making up the data set for *Health Care Including Bioimaging*, 27% identified accuracy as the single most important measurement problem. This was followed by lack of fundamental knowledge (15%). The *measurement problems* identified in the RMNs are consistent with those identified in the case studies, i.e., 31% identified lack of fundamental knowledge; and 20% identified accuracy. Nearly a third of *measurement solutions* identified represent the development of standards and measurement technologies. Government laboratories and agencies together with NMI were the major *solution providers* identified in the measurement

needs (a total of 52%). The next-largest grouping was industry R&D laboratories, industry partnerships, and instrument suppliers (together 26%). Universities were identified as *solution providers* in 12% of the measurement needs.

A *solution* to a principal *measurement problem* impeding technological innovation in *Health Care Including Bioimaging* is to be found through collaboration of industry partnerships with government laboratories and agencies focused on development and use of common standards of measurement.

Thirty-one percent of the measurement needs identified involved both public and private efforts to solve these MNs. However, 50% stated that no efforts were being made by any sector to solve the *measurement problems*. Only 4% identified efforts being made by the private sector alone. There may be a common basis for the identification and pursuit of synergistic solutions to the very basic measurement problem across clinician and researcher communities and stages of technological innovation.

Solutions to *measurement problems* impeding technological innovation in *Health Care Including Bioimaging* require a multi-disciplinary approach that engages specialists in such areas as chemistry, physics, materials and computer science, and fields of engineering with those in biology and medicine.

Beyond being simply measurements related to biology, chemistry, materials or physics, *Health Care Including Bioimaging* measurements are multi-disciplinary. These barriers and solutions involve all the physical sciences as well as biological sciences. The major *measurands* for health care apply to the human body and biological systems, but the measurement of these systems are made with tools of almost all scientific and engineering disciplines.

Other Observations

- There is a significant need in the *Health Care Including Bioimaging* sector/technology area for measurements and standards (performance standards and predictive tools, computer modeling techniques, biomarkers, and clinical trial endpoints).
- Technology innovation in the *Health Care Including Bioimaging* sector/technology area is strongly associated with measurement innovation, which has a direct impact on the development and application of diagnostic instrumentation and testing. This is motivated by economics and improved quality of life. While regulation partially drives technology innovation, primary factors lie outside of the regulatory environment.

Information Technology (IT) Software

Information Technology Software is the engine that powers a broad range of information technology (IT) products and systems that support business, manufacturing, finance, health care, telecommunications, transportation, defense, research, and most other industrial sectors.

Increasingly, U.S. and global economies rely on *IT Software* products to function properly. The *IT Software* sector/technology area is both dynamic and diverse. In 2005, the U.S. software market grew by 3.9% to a value of $75.6 billion, and is projected to grow at a compound annual rate of 5.8% between 2005 and 2010 to a value of $100.4 billion.

Worldwide revenues for packaged software, not including software development and services, were projected at $205.7 billion in 2005 and $219.8 billion in 2006. The United States is estimated to hold approximately 50% of the world market. With steadily growing demands across most sectors for new software products to meet business requirements, new technological and measurement innovations will be needed to ensure software product innovations continue. Additional information on the *IT Software* sector/technology area can be found in Appendix F.

Among the technological innovations in *IT Software* that would benefit from solutions to the *measurement problems* documented in this assessment are next-generation software systems for a variety of applications, including:

- Automated control of complex manufacturing processes.
- Computer-assisted diagnoses from medical images and data.
- Intelligent robotic systems for material defense and homeland security.
- High-security analysis and transfer of financial, health care, and other private data.
- Next-generation Internet and Web services.

Data and Results

The set of software and IT measurement needs for this sector/technology area consists of 33 MNs and 50 RMNs; the latter from 16 industry roadmaps. As results for this sector/technology area, the *inferential analysis process* yielded *findings* and *other observations*. The *findings* are firm conclusions verified by industry. The *other observations* are provisional conclusions that are suggested by the MN data and considered to be significant but, because of the limited sample of data, do not rise to the level of *findings*.

Findings

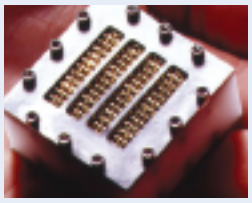
Two-thirds of the MNs in the *IT Software* sector/technology area identified performance measurement (software performance, system performance, or computational performance) as a *measurement problem*—five times as frequently in this area as in all sector/technology areas combined. MNs explicitly stated the need for metrics for characterizing the performance of software systems, while others identified the need for interoperability. RMNs identified both system performance and interoperability as important issues in this sector/technology area.

Performance measurement— in particular measurement of software and system performance, including interoperability— is critical to overcoming the *measurement problems* that pose technical barriers to technological innovation in the *IT Software* sector/technology area.

Other Observations

- Security and cybersecurity—themes identified as cross-cutting in the Technology Roadmap Review—present significant technical barriers requiring measurement innovation. This becomes particularly prominent when moving beyond the applied research *stage of technological innovation*.
- Accuracy, lack of standards, data, acceptability/compatibility, reliability, and lack of fundamental knowledge are key *measurement problems* that pose barriers to technological innovation, particularly during the applied research *stage of technological innovation.*

Materials



The *Materials* sector/technology area includes polymers, metals, ceramics, biomaterials, nanomaterials, building materials, and composites. Measurement needs span a broad spectrum of applications and issues, including primary chemical, physical, and mechanical measurands; manufacturing and processing; and application-specific function (e.g. catalysts, electronics, and building infrastructure). The MNs affect much of the economy and involve technological innovations that have a broad reach, such as those of nanotechnology and manufacturing. Highly capable, accurate, sensitive, low-cost, reliable measurement methods and instrumentation are required to realize the promise of manipulation, imaging, measuring, and modeling strategies upon which construction of complex materials and structures will be achieved.

Among the technological innovations in *Materials* that would benefit from solutions to the *measurement problems* documented in this assessment are:

- Superconducting magnets for magnetic resonance imaging (MRI).
- Nanocomposite materials with increased thermal stability and reduced flammability.
- High-accuracy dies for the production of sheet metal-formed automotive body parts.
- New classes of body armor using advanced fibers.
- Advanced scanning probe microscopy (SPM) techniques for nanoscale mapping of chemical, mechanical, thermal, and electro-optical properties.

Data and Results

The set of measurement needs for this sector/technology area consists of 40 MNs and 68 RMNs, the latter from 17 roadmaps. As results for this sector/technology area, the *inferential analysis process* yielded *findings* and *other observations*. The *findings* are firm conclusions verified by industry. The *other observations* are provisional conclusions that are suggested by the MN data and considered to be significant but, because of the limited sample of data, do not rise to the level of *findings*.

Findings

A principal *measurement problem* in the *Materials* sector/technology area is the absence of measurement instruments and methods capable of accurately characterizing the behavior of complex materials systems and structures.

Among the MNs in this set were accuracy (53%), data and data collection and/or retrieval (43%), lack of fundamental knowledge (30%), and resolution (28%). Development of measurement technology and measurement methods were the two most commonly cited measurement solutions at 40% each. This combination is interpreted as an indicator that many current measurement techniques for characterization of complex materials systems and structures are meeting fundamental limitations. Adaptation or novel combinations of existing methods will sometimes be sufficient to a point, but many measurement needs have proceeded beyond this stage. Further, the systems nature of these complex materials and structures indicates the need for a systems-level multidisciplinary approach for solutions—i.e., a complex system will possess certain characteristics, such as interfacial behavior, that might not be measurable with current techniques. The replacement of a current measurement technique with another that will overcome a fundamental limit of accuracy and

resolution requires a new measurement method, technique, or instrument. The development of a new measurement instrument, technique, or method, especially if it requires new measurement science, generally requires more research and longer-term effort than does improvement of a current technique.

In the *Materials* sector/technology area, a key factor driving the need for measurement innovation is the anticipated need to evaluate the performance and reliability of new materials successively at the production and market stages of their development.

Reliability is specifically tagged as a *measurement problem* in 13% of MNs. Fifty-five percent of MNs make references to lifetime performance, reliability, and consistency, all factors directly related to prediction of reliability. Additionally, the engineering of reliability into a product would be based on the understanding of the relationship between materials and behavior that comes from overcoming the four most prevalent *measurement problems* identified for this set. They are accuracy, data and data collection and/or retrieval, resolution, and lack of fundamental knowledge.

The timely delivery of measurement solutions in the *Materials* sector/technology area is increasingly challenged by the growing complexity of materials systems and structures and their interfaces.

Complex materials are often a key element of technologically innovative commercial products. Sixty-five percent of *Materials* MNs identified *technological innovations at stake* wherein the products are composed of multiple materials (e.g., metals, ceramics, polymers, nanoparticles), rather than a single component (e.g., a specific grade of steel). Successful measurement solutions will be tailored to address measurements of individual materials as well as the interfaces between materials. The complexities of the materials systems and structures in this set may require different and complex resources over a greater period of time than would be typically needed to address simpler materials systems and structures. Therefore, the average lead time for a new measurement instrument, technique, or method may be greater than in the past. Additionally, a broader spectrum of expertise may be required to deliver a successful measurement solution.

Other Observations

- Significant *measurement problems* impeding *Materials* technological innovations include accuracy, data and data collection and/or retrieval, lack of fundamental knowledge, and resolution.
- The strengthening of industry consortia/partnerships may serve effectively in the identification of *measurement solutions* by increasing the USMS "innovation orientation"—the anticipation and responsiveness of the USMS to *measurement problems* impeding innovation.
- There are anticipated needs without sufficient activity to provide timely *measurement solutions.* Public-private interactions might be a preferred avenue to meet MNs by ensuring that public efforts are timely and appropriate.
- To be most effective, materials measurement providers must anticipate how new materials systems/technologies will be used in order to determine and support MNs.
- Mature materials production industries have measurement needs with a common goal to improve process and production efficiency (cost, time, and energy).

Nanotechnology

The *Nanotechnology* sector/technology area involves the understanding and control of matter with at least one dimension less than 100 nanometers, where unique phenomena enable novel applications. At nanoscale dimensions, the physical, chemical, and biological properties of materials differ in fundamental and valuable ways from the properties of individual atoms and molecules or bulk matter.

The National Science Foundation, in its 2001 publication, *Societal Implications of Nanoscience and Nanotechnology*, predicts that the worldwide market of nanotechnology-related products will exceed $1 trillion annually within 10 to 15 years. Highly capable, low-cost, and reliable measurement methods and instrumentation are required to realize the promise of manipulation, imaging, measuring, and modeling the strategies upon which construction of complex nanoscale devices and machines will be achieved. Additional information on the *Nanotechnology* area can be found in Appendix F.

Among the technological innovations in *Nanotechnology* that would benefit from solutions to the *measurement problems* documented in this assessment are:

- Vastly increased digital data storage capacities.
- Smaller, faster, more power-efficient electronic devices.
- Advanced drug delivery systems.
- High-capacity fuel cells.
- New families of high-performance catalysts, sensors, and activators.

Data and Results

The set of measurement needs for this sector/technology area consists of 36 MNs and 49 RMNs, the latter from 10 roadmaps. As results for this sector/technology area, the *inferential analysis process* yielded *findings* and *other observations*. The *findings* are firm conclusions verified by industry. The *other observations* are provisional conclusions that are suggested by the MN data and considered to be significant but, because of the limited sample of data, do not rise to the level of *findings*.

Findings

Nanotechnology is unique among the sector/technology areas in its high demand for new advanced measurement instrumentation, which is to provide accurate, high-resolution characterization of physical, chemical, and biological properties of materials at the nanometer scale.

The frequency of measurement instrument as a solution is twice as high as average for all of the economic sectors/technologies areas combined. The frequent occurrence of accuracy and resolution together as *measurement problems* (80% and 61% of MNs cited these, respectively) in combination with development of measurement technology, research in measurement science, and measurement instrument together as *measurement solutions* (cited in 70%, 36% and 33% of MNs, respectively) is considered to be significant. These associations suggest a need for new instrumentation considering that *measurement problems* at these dimensions cannot be resolved with existing instrumentation.

Industry is limited not only in its ability to measure key parameters but also in its ability to identify which key parameters must be measured to meet anticipated regulations.

A particular issue in the *Nanotechnology* sector/technology area is the problem of identifying which physical, chemical, and biological

properties of materials at nanometer dimensions are the most important to measure, particularly to satisfy regulatory requirements. U.S. companies aiming to market globally are concerned about foreign regulations, such as the RoHS Directive ("the restriction of the use of certain hazardous substances") that go into effect in Europe in July 2006. Forty-three percent of RMNs cite *measurement problems* associated with environmental health and safety issues. A clear priority was expressed for characterization and understanding of the environmental, biological, and health impacts of using nanomaterials. In the absence of clear indications of what the regulations will be, metrology solutions won't be pursued that would support compliance, and metrology solutions that would quantify risk are being avoided. The absence of these measurements (and the required innovation) will inhibit establishment of public confidence in nanotechnology.

The absence of measurement tools with the capability to measure properties of nanomaterials and nanodevices as they relate to functional performance and to make such measurements at speed are impediments to realization of nanotechnology products.

A prevailing measurement issue in the RMNs in the *Nanotechnology* sector/technology area is that of relating measureable properties of nanodevices, materials, and structures to their functionality and performance. Confidence in production of nanodevices appears to be limited and measurement tools are needed for nanotechnology products to demonstrate their capabilities. The problem is manifested both in the research stage of development of potential products, where most of the activity in Nanotechnology is occurring, and in the production stage, for the limited number of nanotechnology products introduced into the marketplace. Speed of measurement is identified as a *measurement problem* in 25% of MNs. RMNs indicate speed as an issue with their emphasis on the need for measurement for real-time analysis and high-throughput testing in high-volume manufacture.

In total, the measurement capabilities being called for could efficiently handle a large volume of diverse input. Development of such capability is frequently achieved only during the latter stages of the technological innovation process, with measurement needs being fulfilled serially rather than in parallel. This approach may present a roadblock to the timely availability of nanotechnology measurement tools, the absence of which puts technological innovations in the *Nanotechnology* sector/technology area at risk.

Other Observations

- Measurement providers in the public sector that are linked to applied research sectors, production communities, market drivers, and user issues can help to accelerate the innovative process.
- Innovative approaches to the measurement of nanoscale physical and chemical properties are key to technological innovation for nanotechnology, especially in cases wherein the fundamental limits of current measurement techniques are being approached.

Semiconductor Electronics

The Semiconductor Electronics industry greatly affects global economic growth. Just as its strength provides a leading indicator of the world's economic health, advanced semiconductor systems contribute substantially to new business opportunities and growth around the world. The scope of this analysis includes semiconductor memories, microprocessors, signal processors, RF and analog/mixed signal circuits, logic devices, and emerging research devices and materials. However, the scope does not include semiconductors for power electronics used in transportation systems and for optoelectronic components used in telecommunications systems.

The Semiconductor Industry Association's (SIA) annual forecast of global semiconductor sales projects a compound annual growth rate of nearly 10 percent for the forecast period of 2005 through 2008, and worldwide sales of microchips from $227 B in 2005 to $309 B in 2008.

Among the technological innovations in *Semiconductor Electronics* that would benefit from solutions to the *measurement problems* documented in this assessment are next-generation semiconductor products that include:

- Logic devices.
- Microprocessors.
- Computer data memories.
- Signal processors.
- RF and analog/mixed signal circuits.
- New types of semiconductor materials, devices, and systems emerging from research.

The rapid introduction of new materials, processes, and three-dimensional structures places great demands on metrology. The lag time between the availability of new measurement techniques for manufacturing and their high-volume production begins has decreased substantially. In the past, measurement techniques were two or more generations ahead of the technology being used for production. This is not the case today. In some instances, lack of measurement techniques inhibits progress, especially for deploying new products.

Data and Results

The set of measurement needs for this sector/technology area consists of 52 MNs and 34 RMNs, the latter from one roadmap. As results for this sector/technology area, the *inferential analysis process* yielded *findings* and *other observations*. The *findings* are firm conclusions verified by industry. The *other observations* are provisional conclusions that are suggested by the measurement-need data and considered to be significant but, because of the limited sample of data, do not rise to the level of *findings*.

Findings

In *Semiconductor Electronics* manufacture, the *measurement problem* caused by the slowness of physical measurement can be overcome by greater use of computer simulations.

Validated simulations can be used to predict useful fabrication process conditions and device and circuit behavior. Models can be used along with process equipment control systems to change process conditions during factory operation. All measurements are interpreted by a model or simulation of the measurement event and measurement equipment. Speed is cited as a *measurement problem* 2.5 times more often on a percentage basis in the *Semiconductor Electronics* sector/technology area than for the entire set of case-study MNs. Sixty-eight percent (23 of 34) of RMNs identify the need for improved computer simulations and/or physical and chemical models as a measurement barrier.

A 2004 IDC report concludes that computer simulations coupled with a small number of measurements yield predictive results much faster than a large number of measurements alone and assist in lowering manufacturing costs. In addition, assuming the availability of appropriate data for input into models, accurate simulations can take the place of experimental fabrication of materials, devices, and circuits, which is costly and time consuming. Simulations can help to narrow the focus from a large number of variables that may traditionally be handled in a design of experiments, to performing a much smaller set of experiments.

New measurement instrumentation developed from pre-competitive R&D is needed to address the principal *measurement problems* that pose barriers to technological innovation identified in the *Semiconductor Electronics* sector/technology area.

Three-fourths of the *Semiconductor Electronics* MNs (38/52) cite accuracy as the *measurement problem*. The combination of accuracy, resolution, and lack of fundamental knowledge as a *measurement problem* and development of measurement technology and measurement instruments as *measurement solutions* is interpreted to indicate that fundamental new measurement technology, particularly new high-resolution, high-accuracy instruments are required. Together, government laboratories and agencies, including NIST as an NMI, are identified as *solution providers* nearly half the time (72/146). Industry consortia/partnerships are the third most frequently identified *solution providers*. They are cited in 40% of the MNs (22/52). The high frequency of these solution providers is interpreted to indicate the pre-competitive nature of development of the measurement technology seen as the solution to the *measurement problem*. The public sector (in collaboration with the private sector), particularly industry consortia/ partnerships, is viewed as a means to the development of pre-competitive measurement technology.

Other Observations

- Domestic companies with *measurement problems* are becoming increasingly dependent on foreign companies to be providers of the solutions to those problems. To remain at that cutting edge of technological innovation, they must be party to the solving of *measurement problems*. Such dependence on foreign companies as providers of solutions in which they are not part is a threat to the U.S. global leadership in this industry and ultimately to the viability of these domestic companies.
- The combination of 3D high-resolution, high-accuracy measurements and of modeling, simulation, visualizing, and extracting useful information from massive data sets will decrease the response-time of the USMS and assist technology innovators to be more productive and stronger competitors; especially, as accurate yield predictions are developed for reliable, high-volume manufacturing of next-generation products.
- The absence of robust theoretical-computational models and computer simulations that accurately predict the behavior and performance of nanoscale semiconductor materials and devices is a major *measurement barrier* to technological innovation. Modeling and simulation are practical alternatives to physical measurements alone.